Why I am excited about working on DAMIC-M in 10 minutes

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for New Perspectives 2020

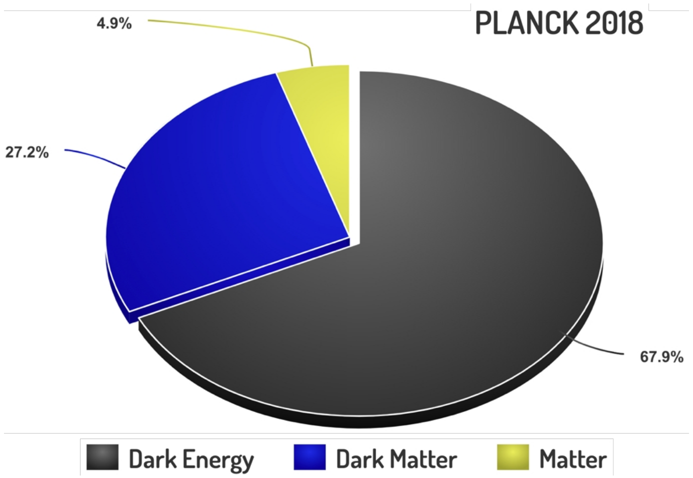
Dark matter introduction

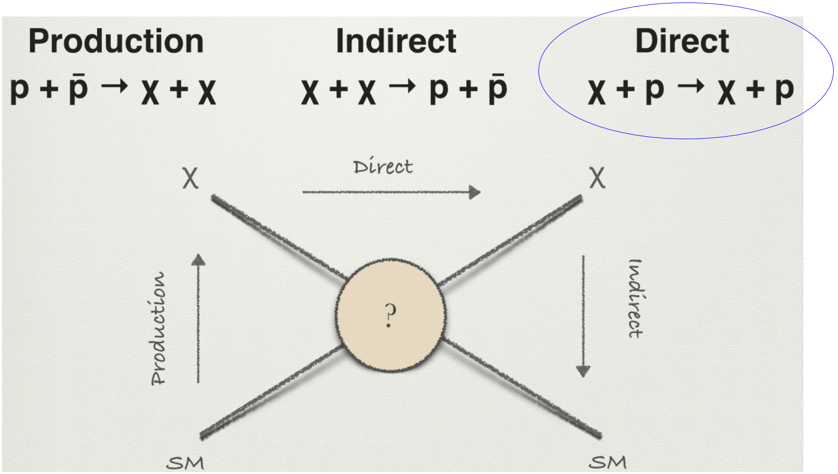
Dark Matter

Not electromagnetically interacting

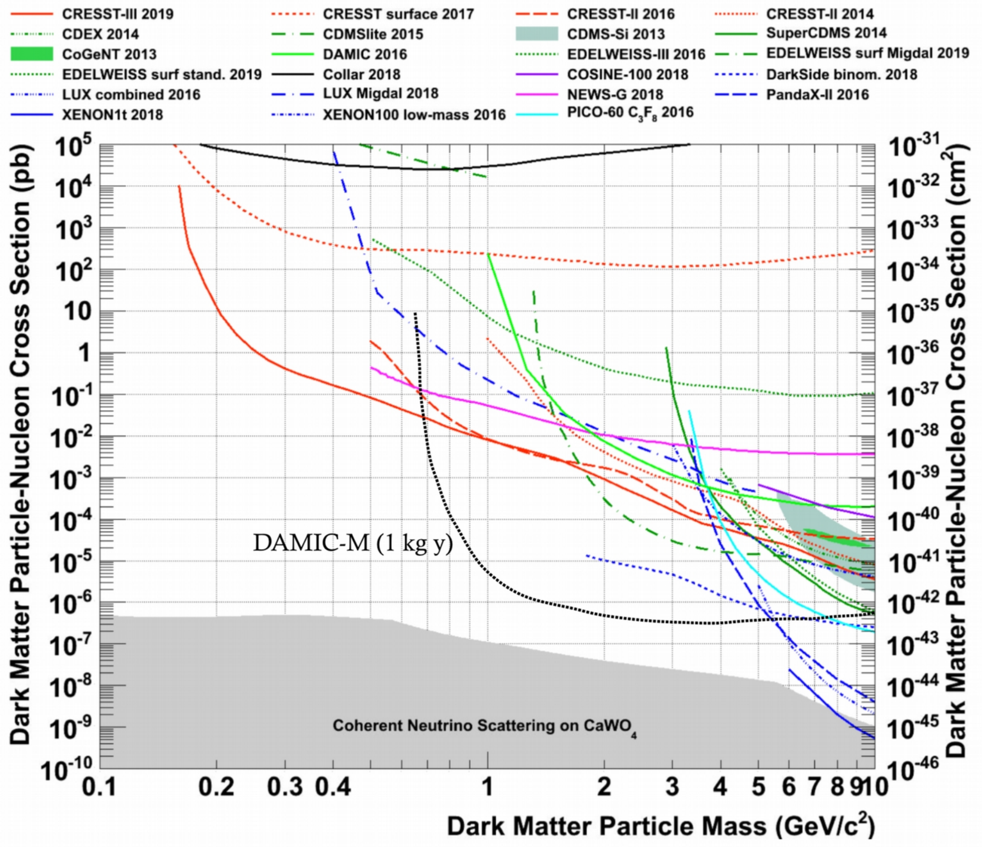
Gravitationally interacting like matter

- WIMP(s): Weakly Interacting Massive Particle(s)





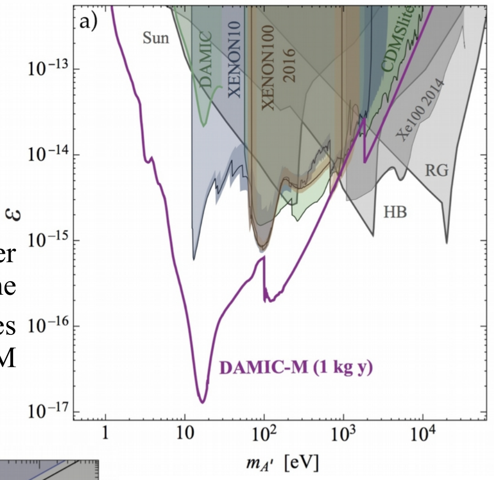
DAMIC-M expected limits



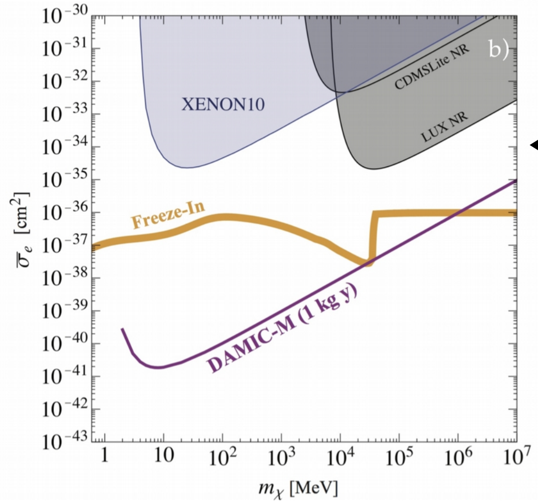
Spin-independent DM-nucleon scattering cross section vs DM mass

Original plot from: *First results from the CRESST-III low-mass dark matter program, 2019, arXiv:1904.00498v1* and drawn line for DAMIC-M

Kinetic mixing parameter vs $m_{A'}$ assuming that the dark photon constitutes all of the DM



Plots from the DAMIC-M proposal in 2017.



DM-electron cross section vs m_χ for a light A' mediator ($m_{A'}$ << keV)

DAMIC-M overview

To achieve these limits:

Massive detector

Very low threshold &
Single e^- resolution

Very low
background
(cosmic bg & radioactivity)

DAMIC-M overview

To achieve these limits:

DArk Matter In CCDs at Modane (DAMIC-M):
- Direct dark matter detection
- Low mass WIMPs and hidden sector DM

Massive detector
- Scientific grade **C**harge-**C**oupled **D**evices with a total target mass of ~1kg

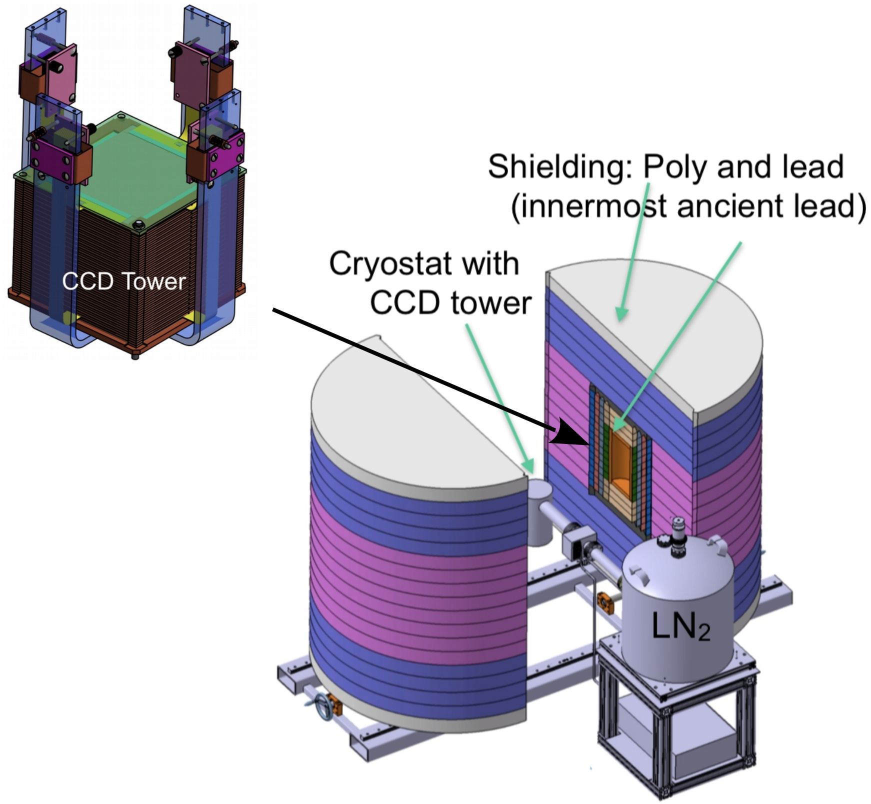
Very low threshold & Single *e⁻* resolution
- CCDs with Skipper readout implementation
- R&D of a novel acquisition system

Very low background
(cosmic bg & radioactivity)
- Radiopure materials for construction & shielding ~0.1 events/(keV kg day) = 0.1 dru
- Placed in Underground Laboratory at Modane

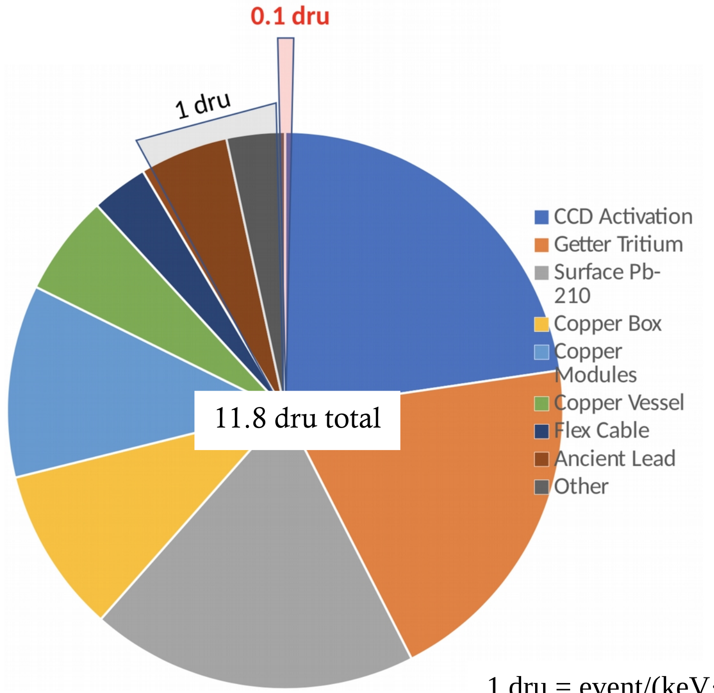
DAMIC at Modane - 2022

- ~2km of rock to stop cosmic bg
- Radon free air supply

Shielding & Background



DAMIC @ SNOLAB background = 11.8 dru
DAMIC-M background goal = fraction of 1 dru

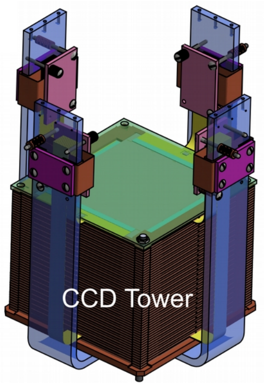


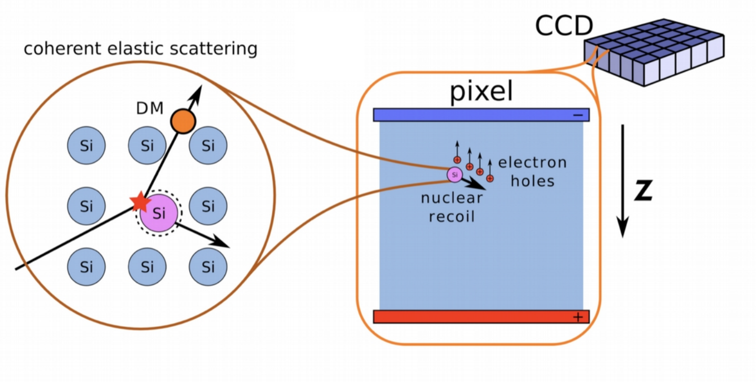
1 dru = event/(keV·kg·day)

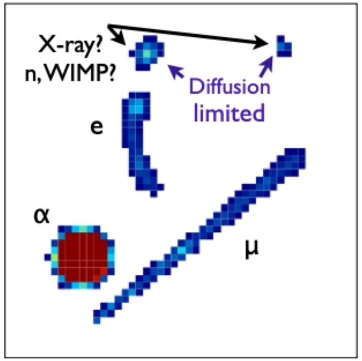
DAMIC-M CCDs

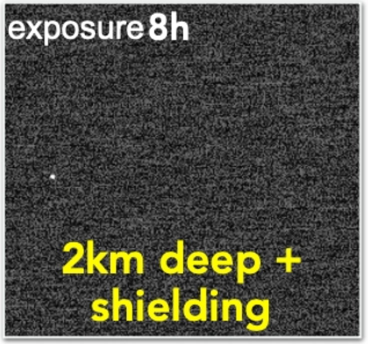
Scientific-grade Charge Coupled Device (CCD) made of pure n-type Si

- 50 CCDs in a tower with a total target mass ~1kg
- Most massive CCDs ever built: 36Mpix large with a pixel area of 15μm x 15μm and 675μm thick, ~20g each
- 3D reconstruction of the incident point using the charge packet diffusion

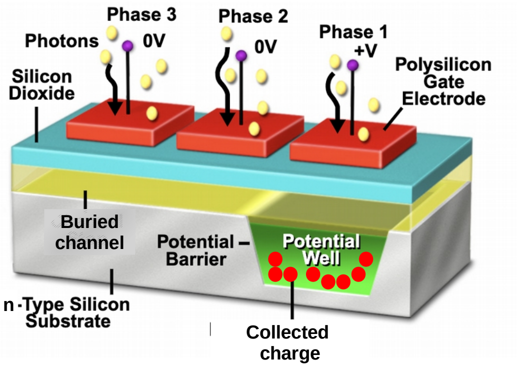






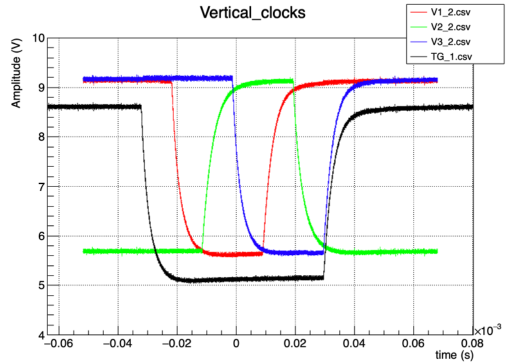


CCD Operation



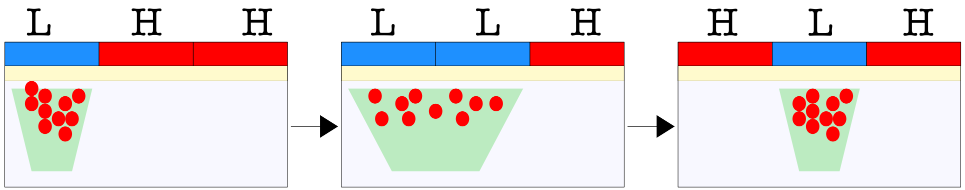
CCD single pixel.

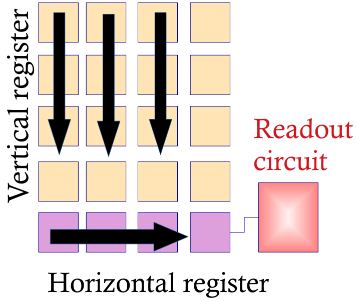
- Charge collection under active electrode
- n-type Si: collected charge → holes
- **Dark current**: thermally generated charge in the bulk of the silicon

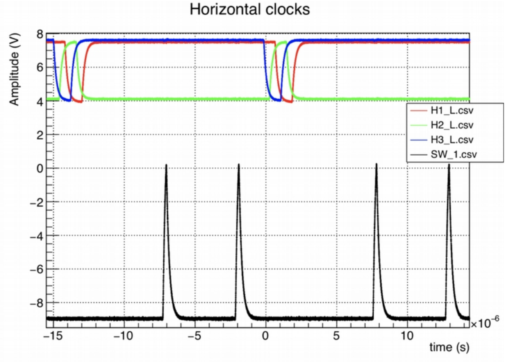


<u>Charge Transfer</u>

- Move the charge by alternating the voltage of the electrodes (clocks) to the Readout circuit





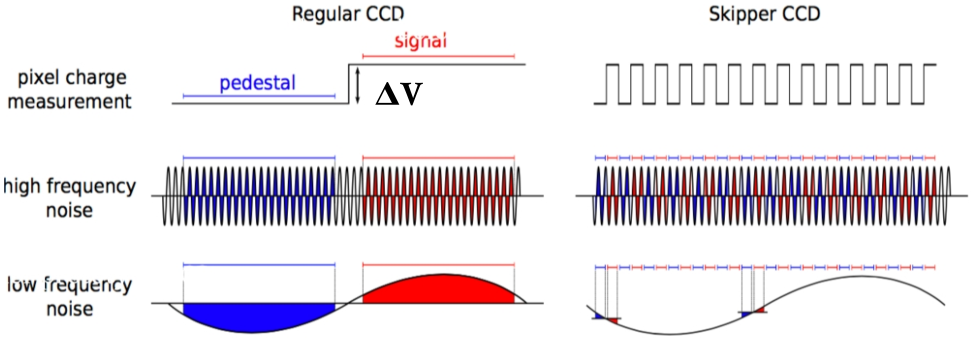


- **Clock noise**: lose or gain charge if the clocks are not well defined

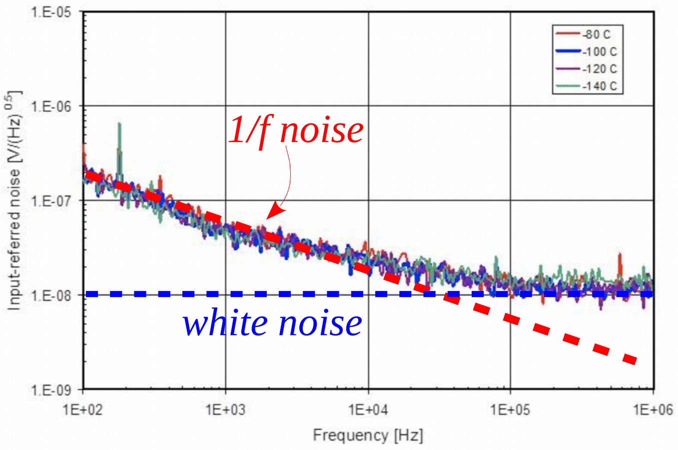
New electronics: 4CABAC board

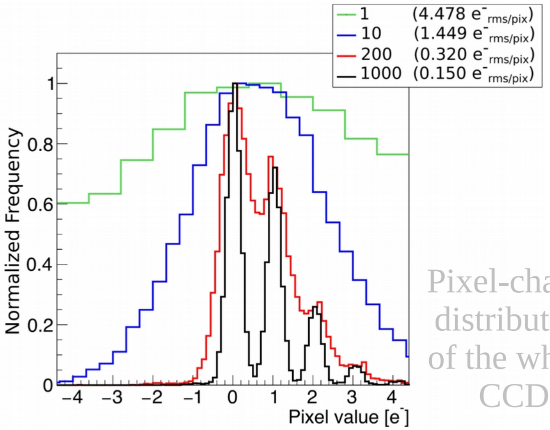
Skipper CCDs – sub-e^- resolution

- **Regular** CCD: single skip integration time O(**10μs**)
  - → high frequency noise is eliminated
  - → low frequency noise dominates (1/f noise)
- **Skipper** CCD: single skip integration time O(**1μs**)
  - → **multiple measurements of the pixel charge**
  - → low frequency noise eliminated
  - → single measurement of low resolution

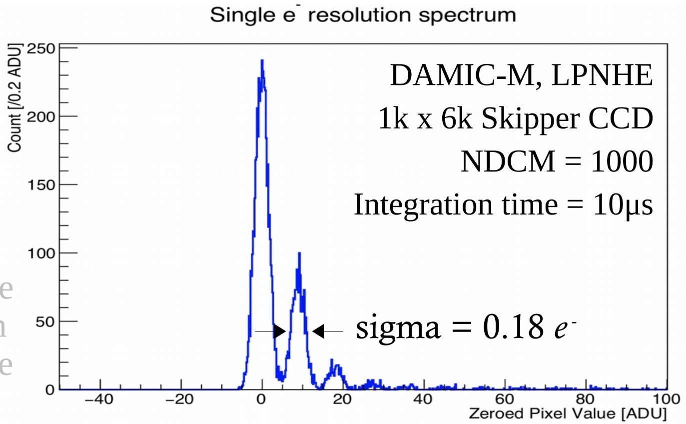


- Output noise decreases as 1/√NDCM (Non-Destructive Charge Measurements), reaching sub-e^- resolution

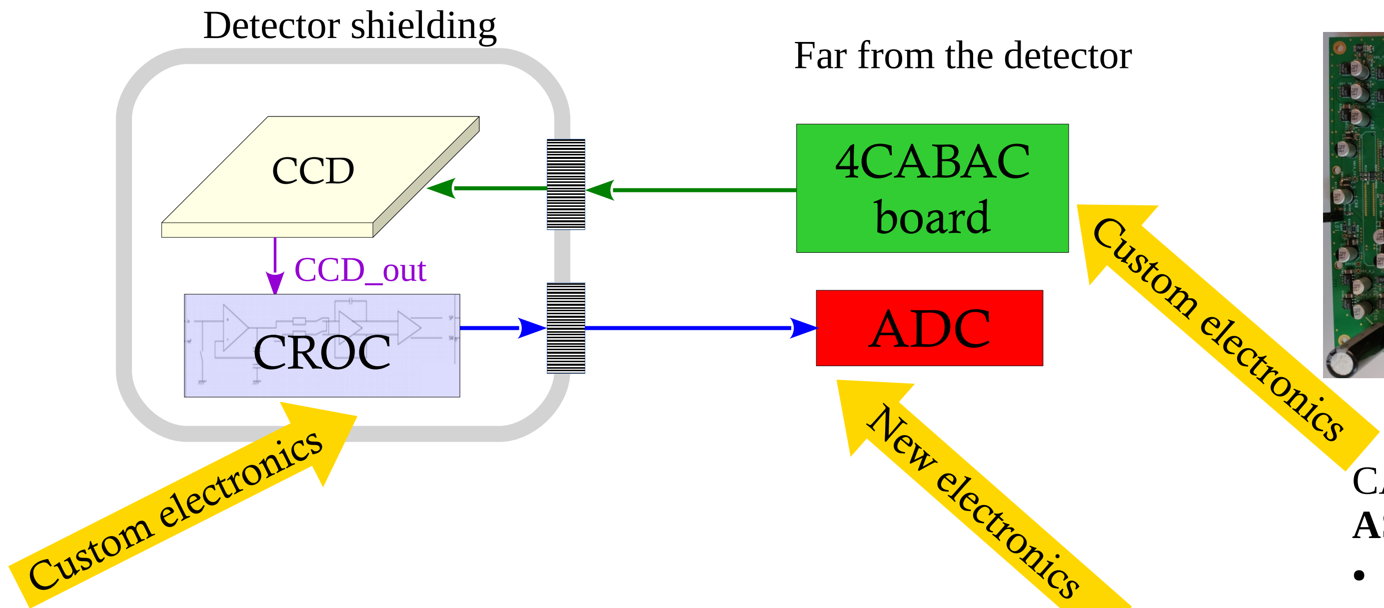


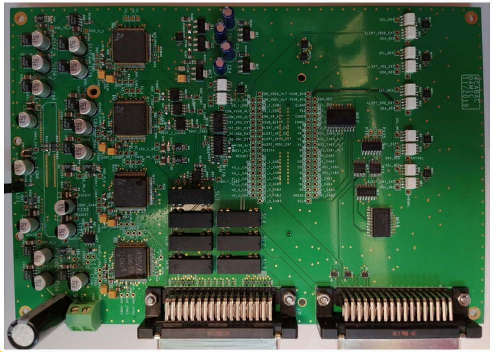


Pixel-charge distribution of the whole CCD



New acquisition system



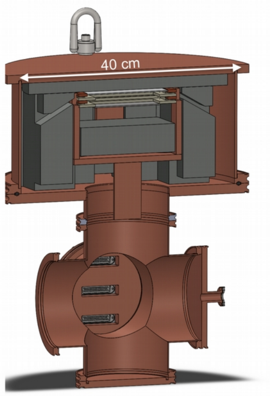


CROC: **C**CD **R**ead**O**ut **C**hip
- Low noise
- Amplifies and processes the output of the CCD to improve the SNR
- Minimizes any introduced noise until the ADC

ADC: **A**nalog to **D**igital **C**onverter
- High resolution
- Fast sampling

CABAC: **C**locks **A**nd **B**iases **A**SIC for **C**CD
- Provides the necessary clocks and bias voltages for the CCD operation
- Performs the sequencing of the clocks

Timeline



Activities:
- Background studies
- Large CCD packaging
- **R&D of the new electronics**
- **Production of the sequencer for the CCD operation**
- **Operate the CCD with the new acquisition system**

Low Background Chamber (LBC): Installation of a smaller detector with ~25g of CCD at LSM.

Objectives:

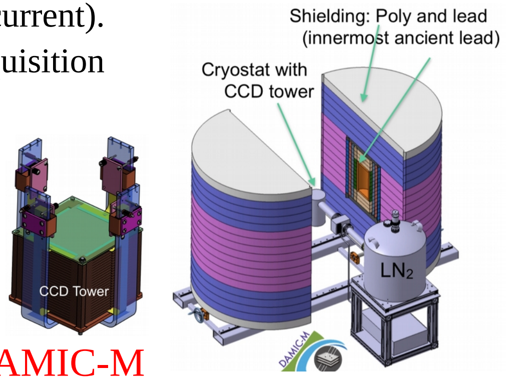
- characterization of DAMIC-M CCDs (dark current).

- Test the new electronics and the overall acquisition system.

- Measurements of background at LSM.

- First scientific results.

- Start operation in 2021



Installation of DAMIC-M

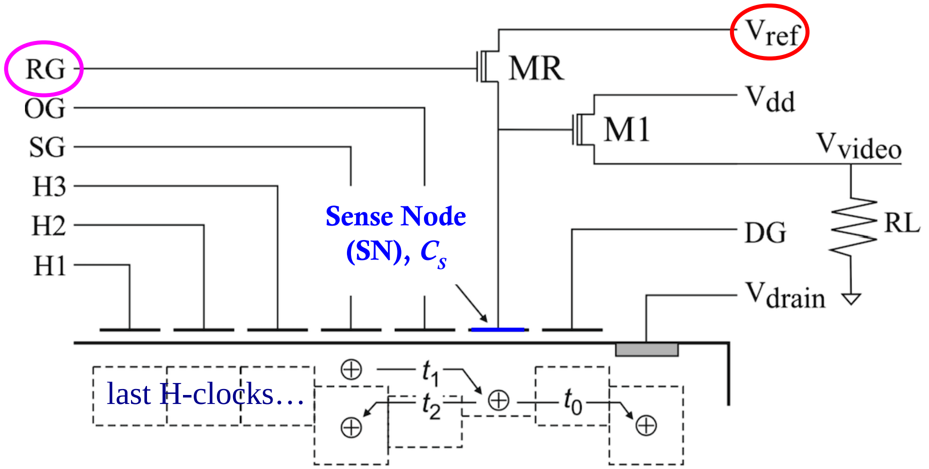
July 2020 (today) | 2021 | 2022 | 2023

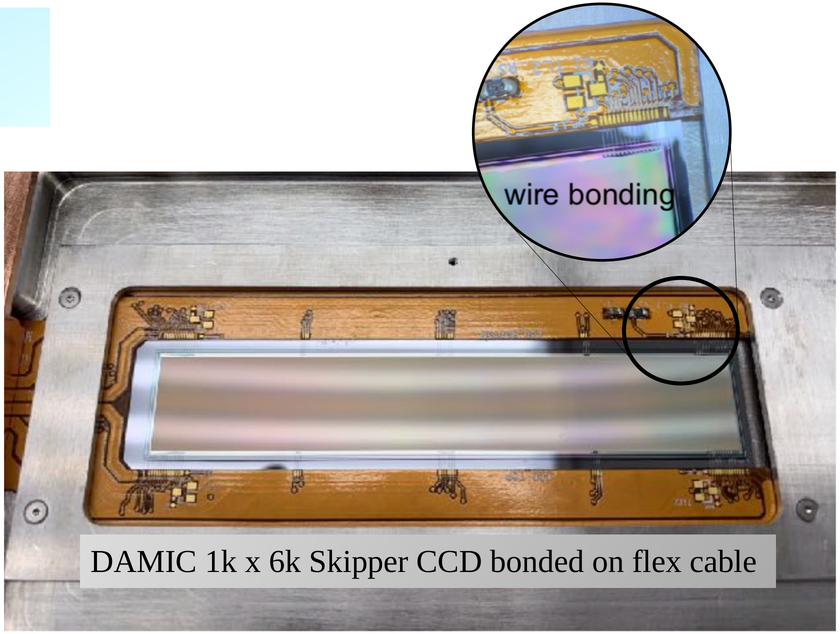
… STAY TUNED

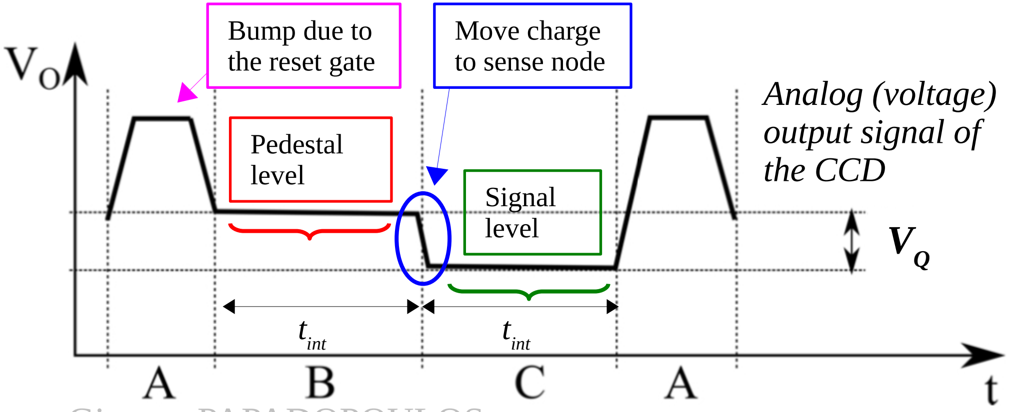
References :
[1] *DAMIC-M Experiment: Thick, Silicon CCDs to search for Light Dark Matter*, N. Castello-Mor for the DAMIC-M Collaboration, 2020

Extra slides

CCD readout circuit







Analog (voltage) output signal of the CCD

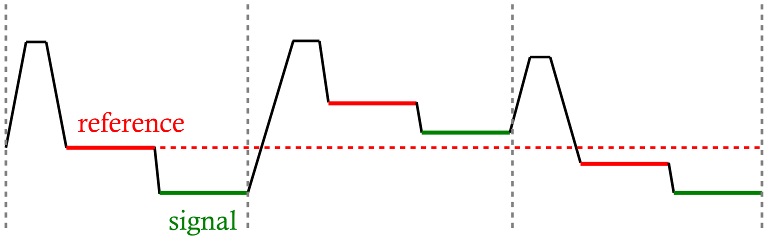
Reaching the end of the CCD, there is a circuit to convert the pixel charge into voltage.

- The Reset Gate sets the Sense Node at a voltage reference value. This will cause a bump in the output signal which will decay quickly, resulting in an outcome reference level *around* Vref.
- The charge Q is injected to the SN changing the voltage by $\boldsymbol{V_Q = Q / C_s}$, where C_s is the capacity of the sense node which is known.
- Measure and subtract the reference and signal levels to find the $\boldsymbol{V_Q}$.

CCD noise sources

Reset or *kT/C* noise

- After reset pulse thermal noise is generated by the resistance of the reset FET. The small capacitance of the Sense Node ~fF leads to a significant uncertainty of the reference level.
- *Correlated Double Sampling* (CDS): measure both the reference and signal levels and subtract them to eliminate the reset noise.



Dark current

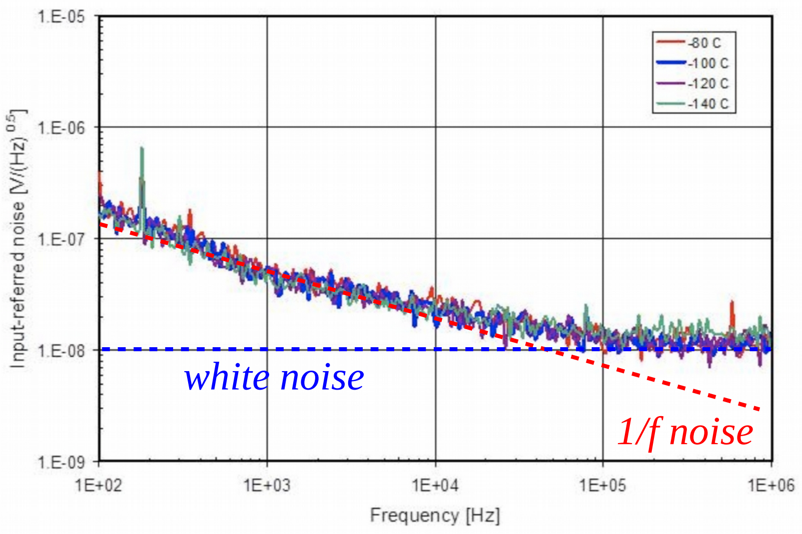
- Thermally generated electrons in the bulk of the CCD
- Linear dependence on time → limits the exposure duration. The longer the exposure, the worse the Signal to Noise Ratio.
- Lower the temperature (~100-140K) to decrease the dark current

Flicker or *1/f* noise

- Source: generated traps in the output MOSFET
- The faster the readout frequency of the CCD, the less the contribution of the flicker noise.
- Dominant up to ~0.1MHz readout speed

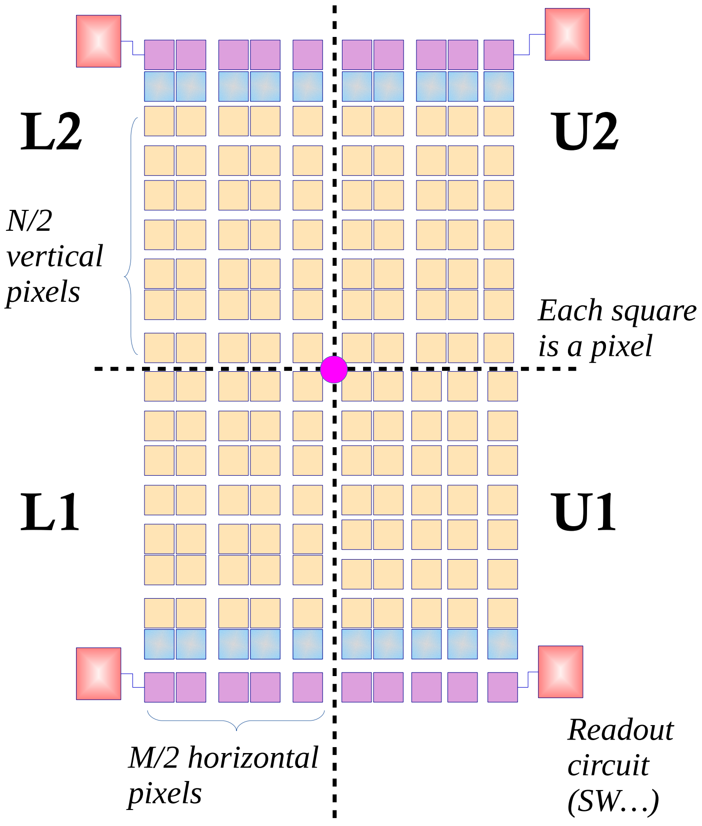
White noise

Thermal noise generated by the output amplifier MOSFET.

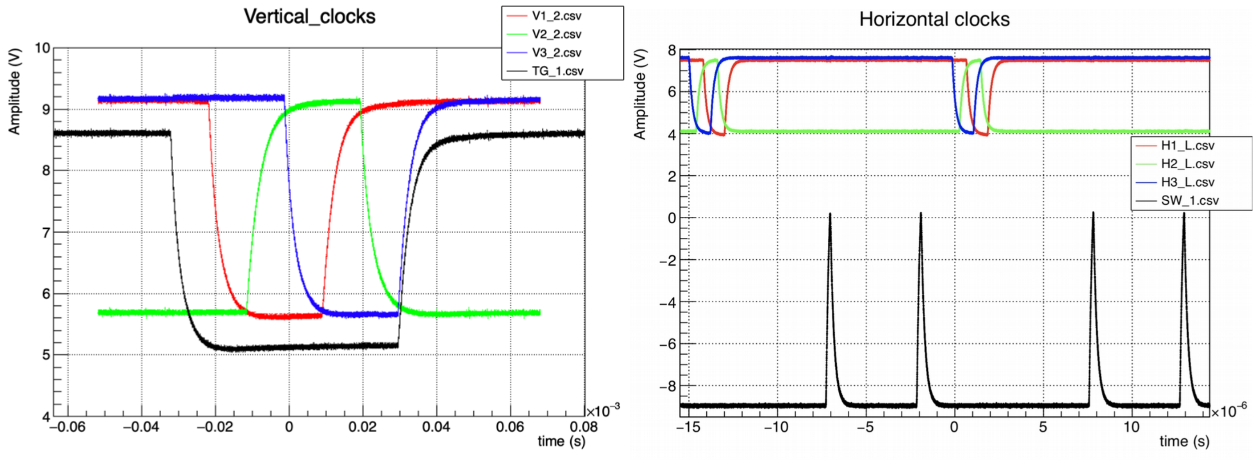


Sequencer for DAMIC-M CCDs

- The total readout time increases linearly with the skips per pixel
- **Dark current!** (thermal noise generated in the silicon bulk of the CCD) limits the exposure period of the CCD weakening the Signal-to-Noise Ratio (SNR)
  - DAMIC-M CCDs have 4 readout circuits to decrease the total readout time
  - Precise signals (clocks) move the charge in the most efficient way



Schematic of DAMIC-M CCD

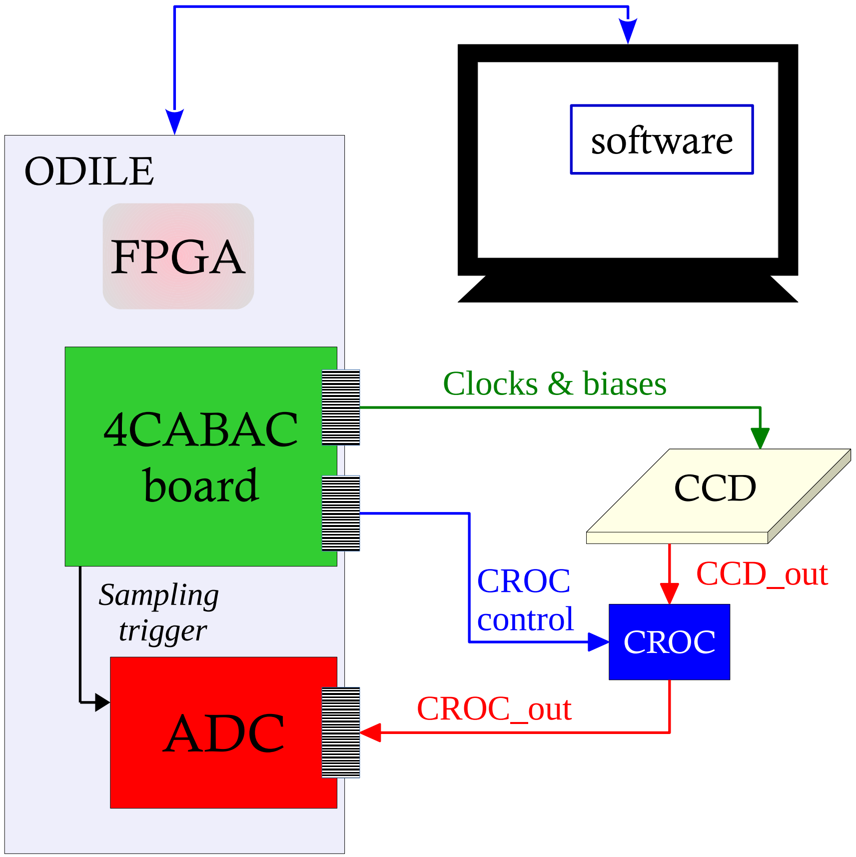


Examples of clocks

New Electronics

The CCD is placed in a cryostat and is controlled and readout by external electronics.

- All voltages and clocks during the expose and readout phases will be provided by the **Clocks And Biases ASIC for CCD** (**CABAC**) board.
    - A **sequencer** implemented in the software will define the 4CABAC board output for the control of the CCD and the CROC.
- **CCD ReadOut Chip** (**CROC**): amplifies and processes the signal to improve the Signal-to-Noise Ratio.
- **Analog to Digital Converter** (**ADC**): performs the transition from the analog to the digital domain.
- Everything is controlled by the **Online Digital Interface for Low-noise Electronics** (**ODILE**) motherboard.



CROC: Transparent mode

The CROC operates as a simple single-to-differential gain amplifier. The output signal shape will be similar to the CCD's, just amplified.

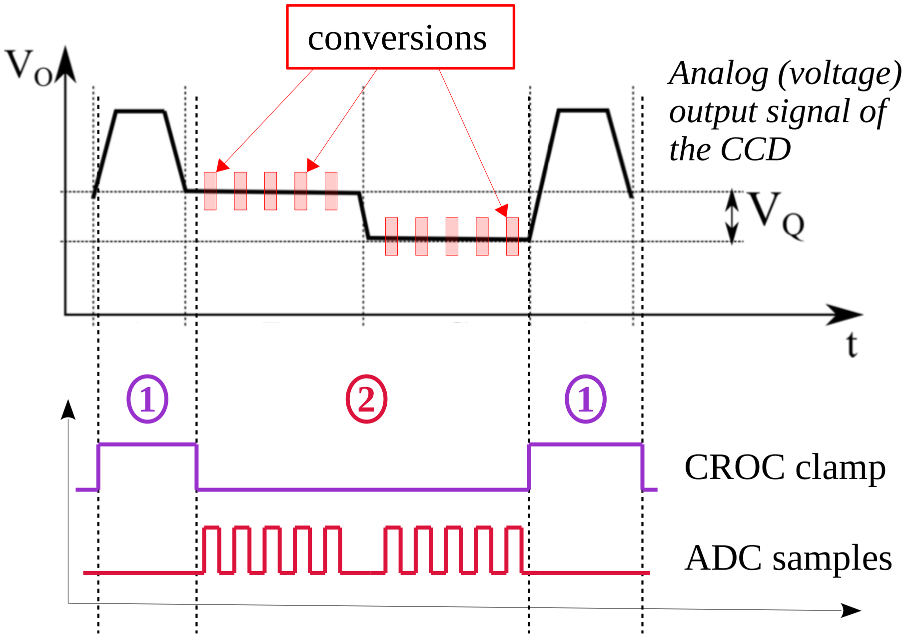
Basically, the ADC oversamples the reference and signal levels.

Advantages

- Digitally determination of the reference and signal level by averaging a sufficient number of samples → *Digital CDS* (DCDS)
- Further digital analysis is possible.

Challenges

- Large number of data to process with Firmware and later on in analysis.



CROC: DSI mode

The DSI is the dominating mode to be used for the pixel charge measurement. The DSI method combines a *Correlated Double Sampling* and a CCD signal integration.

1) A **reset pulse** sets the CROC input to a voltage reference. Same principle as for the CCD conversion of charge.

2) As the reference level stabilises, the CROC amplifies and **integrates** this level for an integration time t_{int}

3) The CROC input is isolated while the pixel charge is injected to the Sense Node of the readout circuit.

4) When is stable, the signal level is **integrated** for the same integration time with **reversed polarity** *with respect to the reference level (achieving the CDS)*

5) The **ADC measures** the output of CROC.

- New measurement with a new **reset pulse…**

Reset → measure reference → measure signal → Sample with ADC